

## CLAIMS

What is claimed is:

- 1            1. A quantum dot vertical cavity surface emitting semiconductor laser
- 2        (VCSEL), comprising:
  - 3            a first distributed bragg reflector (DBR) mirror disposed on a substrate
  - 4            layer comprised of a first plurality of mirror pairs with each mirror pair
  - 5            including layers having a step change in indices of refraction;
  - 6            a second distributed bragg reflector (DBR) mirror comprised of a
  - 7            second plurality of mirror pairs with each mirror pair including layers having a
  - 8            step change in indices of refraction;
  - 9            a semiconductor quantum dot active region disposed between a top of
  - 10          the first DBR mirror and a bottom of the second DBR mirror, the quantum dot
  - 11          active region including a plurality of quantum dots embedded in a plurality of
  - 12          quantum wells disposed proximate at least one antinode of a longitudinal optical
  - 13          mode, the quantum dots having a corresponding optical confinement factor;
  - 14          first and second doped semiconductor intracavity contact layers each
  - 15          having a thickness of no more than about half a wavelength disposed between
  - 16          the first and second DBR mirrors positioned and doped to inject electron-hole
  - 17          pairs into the quantum dot active region in response to a drive current;

18                   the mirror pairs of at least one of the DBR mirrors comprised of a  
19                   semiconductor layer and an oxidizable semiconductor layer which has been  
20                   oxidized to form a material with a refractive index substantially lower than the  
21                   unoxidized semiconductor, increasing the reflectivity of the mirror; and  
22                   at least one mode control layer disposed between the top of the first  
23                   DBR mirror and the bottom of the second DBR mirror forming a refractive index  
24                   profile to increase optical confinement of the quantum dot active region and  
25                   reduce optical confinement in the contact layers.

1                   2. The VCSEL of claim 1, wherein the number of quantum dot layers,  
2                   the optical confinement of the quantum dot layers, and an optical overlap in  
3                   doped contact layers is selected to achieve a threshold gain that is less than a  
4                   saturated gain of a ground state of the quantum dots over a temperature range  
5                   between about 0 °C to about 85 °C.

1                   3. The VCSEL of claim 2, wherein the active region has a longitudinal  
2                   thickness that is about an integer number of half wavelengths in the laser at a  
3                   target emission wavelength.

1                   4. The VCSEL of claim 1, wherein each mode control layer has a  
2                   longitudinal thickness of about one quarter of the emission wavelength in the  
3                   laser, has a refractive index different that adjacent layers, and is positioned in the  
4                   cavity to form a resonant reflection acting to increase the longitudinal mode

5 intensity in the quantum dot active region and decrease the longitudinal mode  
6 intensity in the contact layers.

1           5. The VCSEL of claim 4, wherein there is a first mode control layer  
2 disposed between a first end of the active region and the first mirror and a  
3 second mode control layer disposed between a second end of the active region  
4 and the second mirror.

1           6. The VCSEL of claim 5, wherein each mode control layer is disposed  
2 between an end of the active region and a heavily doped contact layer.

1           7. The VCSEL of claim 1, wherein the second DBR mirror comprises  
2 mirror pairs having an oxide layer and a semiconductor layer.

1           8. The VCSEL of claim 7, wherein the first DBR mirror comprises  
2 mirror pairs having a semiconductor layer and an oxidizable semiconductor  
3 layer with at least one opening is formed in the first DBR mirror through the  
4 oxidizable semiconductor layer to laterally oxidize the oxidizable layers with a  
5 laterally connecting portion of the first DBR mirror along at least one side of the  
6 first DBR mirror to inhibit delamination of the first DBR mirror.

1           9. The VCSEL of claim 1, wherein the at least one DBR mirror  
2 comprised of a semiconductor layer and an oxidizable semiconductor layer  
3 further comprises: an intermediate layer disposed between the semiconductor

4 layer and the unoxidizable semiconductor layer having a composition selected to  
5 inhibit delamination of the oxidized DBR mirror.

1 10. The VCSEL of claim 8, wherein the substrate is a GaAs substrate  
2 and the quantum dots comprise self-assembled InAs quantum dots formed in  
3 InGaAs quantum wells, and the DBR mirrors layers comprise alternating layers  
4 of  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  and  $\text{Al}_y\text{Ga}_{1-y}\text{As}$ , where  $x$  is greater than  $y$ .

1 11. The VCSEL of claim 10, wherein the Al molar fraction of the  
2  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer is selected to be between about 0.95 to 0.99 whereby the  
3 oxidation rate of the  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  layer is controlled.

1 12. The VCSEL of claim 1, wherein there is a first mode control layer is  
2 disposed between a first end of the active region and the first mirror and a  
3 second mode control layer disposed between a second end of the active region  
4 and the second mirror, each mode control layer having a longitudinal thickness  
5 of about one quarter of the emission wavelength in the laser, has a refractive  
6 index different than adjacent layers, and is positioned to form a resonant  
7 reflection acting to increase the longitudinal mode intensity in the quantum dot  
8 active region and decrease the longitudinal mode intensity in the contact layers.

1 13. The VCSEL of claim 12, wherein each mode control layer has a  
2 refractive index lower than adjacent layers.

- 1        14. The VCSEL of claim 13, wherein the active region has a thickness that is  
2        approximately an integral number of half wavelengths in the laser.
- 1        15. The VCSEL of claim 12, wherein each mode control layer has a refractive  
2        index higher than adjacent layers.
- 1        16. The VCSEL of claim 15, wherein the active region has a thickness that is  
2        approximately an odd number of quarter wavelengths.
- 1        17. A vertical cavity surface emitting semiconductor laser (VCSEL),  
2        comprising:  
3              a first distributed bragg reflector (DBR) mirror;  
4              a second distributed bragg reflector (DBR) mirror spaced apart from  
5        the first mirror to form a microcavity for a longitudinal optical mode;  
6              a semiconductor quantum dot active region having a first end and a  
7        second end disposed in the microcavity between the mirrors;  
8              first and second doped semiconductor intracavity contact layers  
9        disposed in the microcavity on opposed ends of the quantum dot active region  
10        doped to inject electron-hole pairs into the quantum dot active region in response  
11        to a drive current;  
12              at least one mode control layer disposed in the microcavity;  
13              the at least one mode control layer having a refractive index profile for  
14        generating reflections within the microcavity which create a resonance condition

15 that increases optical confinement in the active region and decreases optical loss  
16 in contact layers.

1       18. The laser of claim 17, wherein each mode control layer is approximately  
2 a quarter of a wavelength in thickness and has a refractive index profile different  
3 than adjacent layers.

1       19. The laser of claim 18, wherein each mode control layer is disposed  
2 between the active region and a heavily doped portion of a contact layer.

1       20. The laser of claim 17, wherein at least one of the DBR mirrors is an  
2 ultrahigh reflectivity DBR mirror formed by laterally oxidizing DBR mirror pair  
3 layers that include an oxidizable semiconductor layer and a substantially non-  
4 oxidizable semiconductor layer.

1       21. The laser of claim 20, further comprising an intermediate composition  
2 layer disposed between the oxidizable semiconductor layer and the substantially  
3 non-oxidizable semiconductor layer to inhibit delamination.

1       22. The laser of claim 20, wherein the first mirror is formed into a mesa  
2 laterally oxidized along at least one side; and  
3           the second mirror has its bottom surface disposed on a substrate layer,  
4           the second mirror having at least one cavity disposed through it through which  
5           the second mirror is oxidized and at least one connecting section providing  
6           lateral support.

1        23. The laser of claim 21 wherein the laser has a threshold gain less than a  
2        saturated gain of a ground state of the quantum dots in a temperature range  
3        between about 0 °C and 85 °C.

1        24. A vertical cavity surface emitting laser, comprising:  
2                first and second distributed bragg reflector (DBR) mirror means for  
3                forming an optical cavity between the mirror means having optical feedback;  
4                quantum dot active means disposed within the optical cavity for  
5        providing optical gain responsive to a current;  
6                intracavity contact layer means for proving current to the quantum dot  
7        active means; and  
8                resonant mode control layer means disposed between the mirror  
9        means for increasing the optical confinement of the quantum dot active means  
10      and reducing the optical intensity in the contact layer means.

1        25. The laser of claim 24, further comprising:  
2                delamination inhibition means for inhibiting the delamination of the  
3        high reflectivity mirror means.

1        26. The laser of claim 24, wherein a threshold gain of the laser is less than a  
2        saturated ground state gain over a temperature range between about 0°C to  
3        85°C.

- 1        27. A method of forming a vertical cavity surface emitting laser having an  
2        oxidized bottom distributed bragg reflector (DBR) mirror with lateral support,  
3        comprising:  
4            etching at least one opening into mirror layers of the bottom DBR mirror,  
5        the at least one cavity disposed proximate an outer perimeter of a lasing portion  
6        of the bottom DBR mirror with at least one lateral connecting portion of the  
7        mirror layers remaining to support the lasing portion of the mirrors; and  
8            laterally oxidizing the mirror layers of the bottom DBR mirror.
- 1        28. The method of claim 27, wherein the bottom DBR mirror includes  
2        AlGaAs layers and the mirror layers are oxidized in steam.
- 1        29. The method of claim 28, wherein the mirror layers comprise AlAs/GaAs  
2        layers laterally oxidized to AlO/GaAs.
- 1        30. The method of claim 29, further comprising an intermediate  
2        composition layer disposed between the AlAs and GaAs layer.
- 1        31. The method of claim 30, wherein the AlAs layer comprises a molar  
2        fraction of gallium of at least about 0.01 for improved control of lateral oxidation  
3        rates.
- 1        32. A vertical cavity surface emitting laser fabricated by the method of  
2        claim 27.

1        33. A method of forming a vertical cavity surface emitting laser with  
2        intracavity contacts from a substrate having a top DBR mirror with DBR mirror  
3        layers, a bottom DBR mirror with DBR mirror layers, a top contact layer, an  
4        active region, and a bottom contact disposed between the mirrors, the method  
5        comprising:  
6              etching a top mirror mesa to expose the top contact layer outside of a top  
7        mirror for the VCSEL;  
8              masking the top mirror mesa and etching down to the bottom contact layer;  
9              etching at least one opening into mirror layers of the bottom DBR mirror,  
10          the at least one opening disposed proximate an outer perimeter of a lasing  
11          portion of the bottom DBR mirror with at least one lateral connecting portion of  
12          the layers remaining to support the lasting portion of the mirrors; and  
13              laterally oxidizing the mirror layers of the bottom DBR mirror through the  
14          at least one opening.

1        34. The method of claim 33, further comprising: depositing a top contact  
2        metallization on a portion of the top contact forming a metal contact on the top  
3        contact layer about the top mirror mesa leading to a contact pad prior to etching  
4        down to the top contact layer.

- 1        35. The method of claim 33, further comprising: depositing a bottom  
2        contact metallization on a portion of the exposed bottom contact layer prior to  
3        etching through the bottom mirror layers.
- 1        36. The method of claim 33, wherein the bottom DBR mirror layers include  
2        AlGaAs layers with an aluminum molar fraction greater than 0.90 and the  
3        AlGaAs layers are laterally oxidized in steam.
- 1        37. The method of claim 36, wherein the bottom DBR mirror layers are  
2        oxidized at a temperature of less than 450 °C.
- 1        38. A vertical cavity surface emitting lasers fabricated by the process of  
2        claim 33.
- 1        39. A vertical cavity surface emitting lasers fabricated by the process of  
2        claim 36.
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